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PROPERTIES OF BOLTS UNDER SHOCK LOADING

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FC

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CONTENTS

ABSTRACT

Four designs of bolts have been prepared from SAE 4140, SAE 1020 hot-rolled, and SAE 1020 cold-rolled steels, and subjected to typical shipboard shock motions while restraining loads of various magnitudes. Bolt designs provided ratios of shank area to thread root area of 1.3/1 and 1/1 in each of two shank lengths. Such quantities as the velocity and acceleration of the restrained load, the velocity of the shock machine anvil table, and the dynamic strain and plastic elongation of the specimen bolt have been measured. Comparisons of static and dynamic stresses and elongations have been made to reveal how their relationship is affected by variation of bolt geometry and material. In general, the use of reduced shanks has been found to result in more desirable shock properties, particularly when the bolt length is fairly great. The improvement is smaller when the bolt length is short. Bolts of SAE 4140 steel have been found usually to possess a more desirable combination of properties than those of the other steels tested.

PROBLEM STATUS

This is a final report on this problem.

AUTHORIZATION

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PROPERTIES OF BOLTS UNDER SHOCK LOADING

INTRODUCTION

Underwater explosion tests have shown that dynamic loads supported by holddown bolts securing heavy equipments were about twice as large as could be carried statically. A series of tests were undertaken to determine what bolt design and material would be most efficient under dynamic conditions when the bolt loading and mechanical shock waveforms approximated field combat conditions. Specific design data were desired for the SMRA-6 diesel engine holddown bolts.

It has long been known that the mechanical properties of materials are affected by the rate of load application. This characteristic has been demonstrated for a variety of materials by authors listed in References 1 through 19. In the specific instance of bolts, it has been shown that reduction of the shank area by diameter reduction, longitudinal flutes, or axial holes, to a value comparable to the thread root area, will greatly increase their ductility and energy-absorbing capacity. Although much effort has been expended in this field, test results are usually not directly comparable, and are often incompatible, principally due to differences in rates of loading, performance criteria, measurement techniques, and to undetermined parameters, such as previous history of the specimen. Test results indicate that not all the mechanisms of dynamic performance are clearly understood, and that it would be difficult to predict a bolt's behavior in a particular dynamic application.

All of the tests cited above have been designed to rupture specimens with a single application of load. Since such an occurrence would be cause for alarm in the case of a bolt restraining essential shipboard equipment, the present tests were designed to investigate the properties of a bolt subjected to repeated impact loadings at stresses below that which would cause rupture during the first blow. The relative quality of the bolts has been judged by comparison of the number of identical impact loadings they can withstand before failure, the average extension per blow, the total elongation, and the maximum dynamic strain. Much of the data included in this report for SAE 1020 cold-rolled steel bolts has been previously reported in Reference 18.

SPECIMENS

The dimensions and designs of the bolts tested are shown in Fig. 1. They are nominal 3/4-in.-diameter bolts with over-all lengths of 2 in. for the short bolts and 4-1/4 in. for the long, and with shank diameters of 0.750 in. for straight-shank bolts and 0.656 in. for reduced-shank bolts. Bolts of each design were machined from hexagonal steel bar stock, SAE 1020 in both the hot and cold-rolled conditions, and SAE 4140 cold drawn and stress relieved. These materials are representative of a group of materials possessing distinguishing metallographic characteristics; 1020 HR (hot rolled) has a well-defined yield point, 1020 CR (cold rolled) exhibits a smooth transition from the elastic to plastic regions without a pronounced yield point, and 4140 is classed as a high-strength steel. The numbers of bolts of each design and material tested are shown in Table A1.* Standard 0.505-in.-diameter tensile specimens were prepared from the bar stock used for each set of bolts and tested statically to assure uniformity of material. The data from these tests are shown as Tables A2, A4, and A6.

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*Tables A1 through A9 are contained in the appendix.

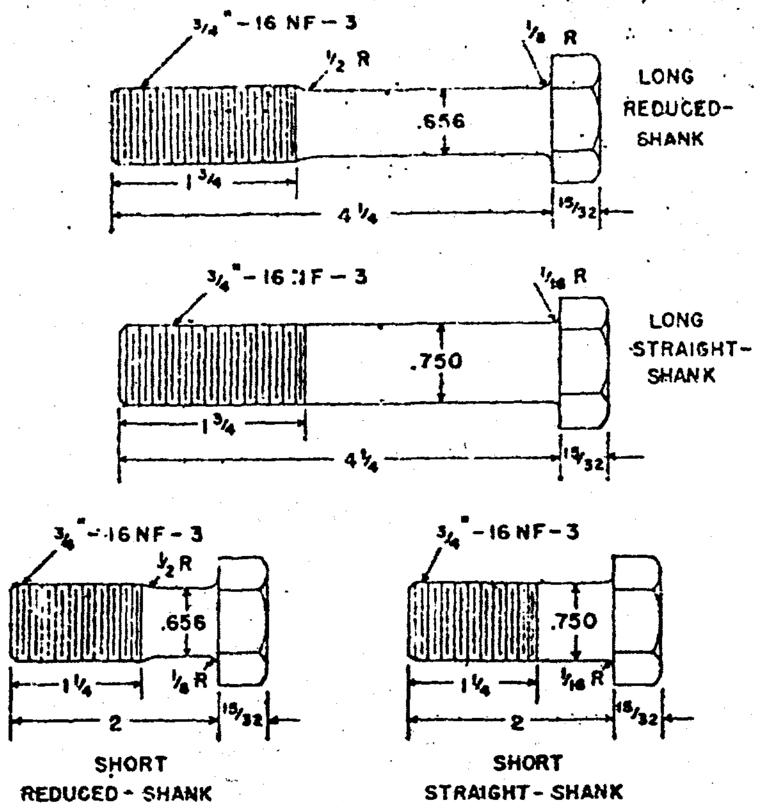


Fig. 1 - Designs of bolts tested

STATIC TESTS

Bolts of each shank type, length, and material were tested statically, with the results shown in Tables A3, A5, and A7. Typical load-strain curves for long reduced-shank bolts of all three materials are shown in Fig. 2. A set of 12 long reduced-shank SAE 1020 CR bolts was examined for evidence of strain-aging. These bolts were subjected to two impact loadings, then aged at room temperature for times ranging from 2 hours to 96 days. They were then given a static tensile test to reveal any change in mechanical properties. Although the elastic limits of all of these bolts were somewhat higher than usual, no correlation was observable between this quantity and the aging time. A series of repeated loading static tensile tests on 0.505-in. specimens of this material revealed no unusual characteristics. All static tests were performed on a hydraulically operated tension-compression testing machine of 60,000-lb capacity. The strain in the bolts was measured by means of an ac bridge circuit incorporating two diametrically opposite strain gages which were located adjacent to the threaded section of the bolts. The apparatus is shown in Fig. 3.

IMPACT TEST PROCEDURE AND APPARATUS

The impact tests were performed on the Navy Mediumweight High-Impact Shock Machine (20). Base plates 17.6 in. diameter and 2 in. thick, and mating weights 17.1 in. diameter and 2 in. thick, were fabricated of hot-rolled steel plate. The weights fitted into recesses in the base plates to eliminate shear and bending forces on the test bolt. The test bolt, which was loaded by the inertial forces of the restrained weight during periods of negative acceleration of the base plate, was consequently subject only to tensile loads. The impact test arrangement is shown schematically in Fig. 4. The length of the tapered bushing was adjusted to provide an initial length of thread engagement equal to one nominal bolt diameter (0.750 in.).

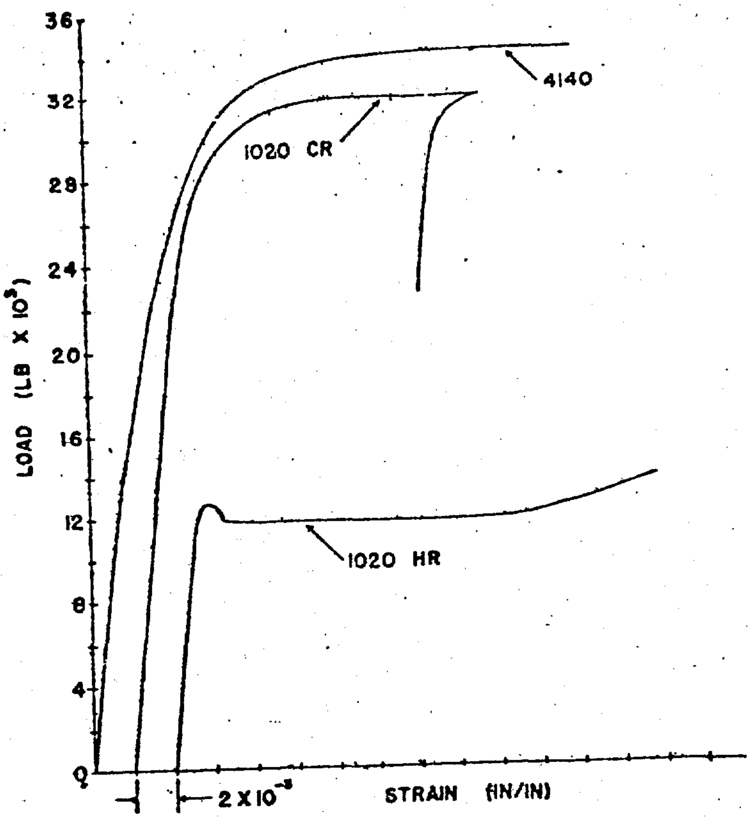


Fig. 2 - Load-strain curves of long reduced-shank bolts of the three materials tested. 4140 indicates SAE 4140, 1020 CR indicates SAE 1020, cold-rolled and 1020 HR, SAE 1020 hot-rolled steels. Strain was measured by an SR-4 gage adjacent to the threads.

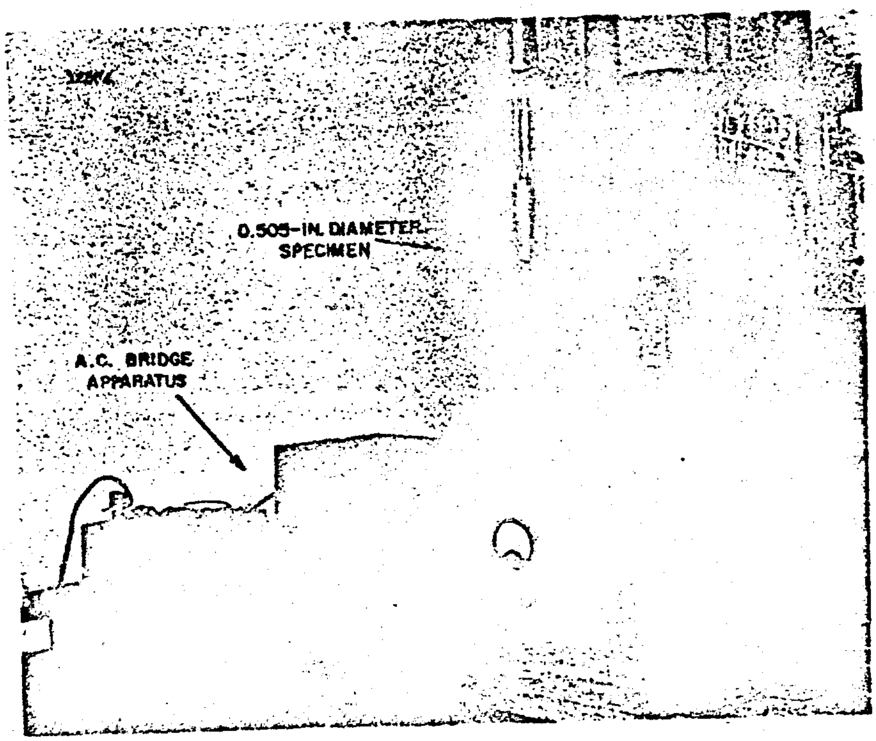


Fig. 3 - Static tensile test apparatus, shown with 0.505-in. specimen under test. All static tests were performed in a hydraulically operated testing machine of 60,000-lb capacity. Strain was measured by an SR-4 gage in an AC bridge circuit.

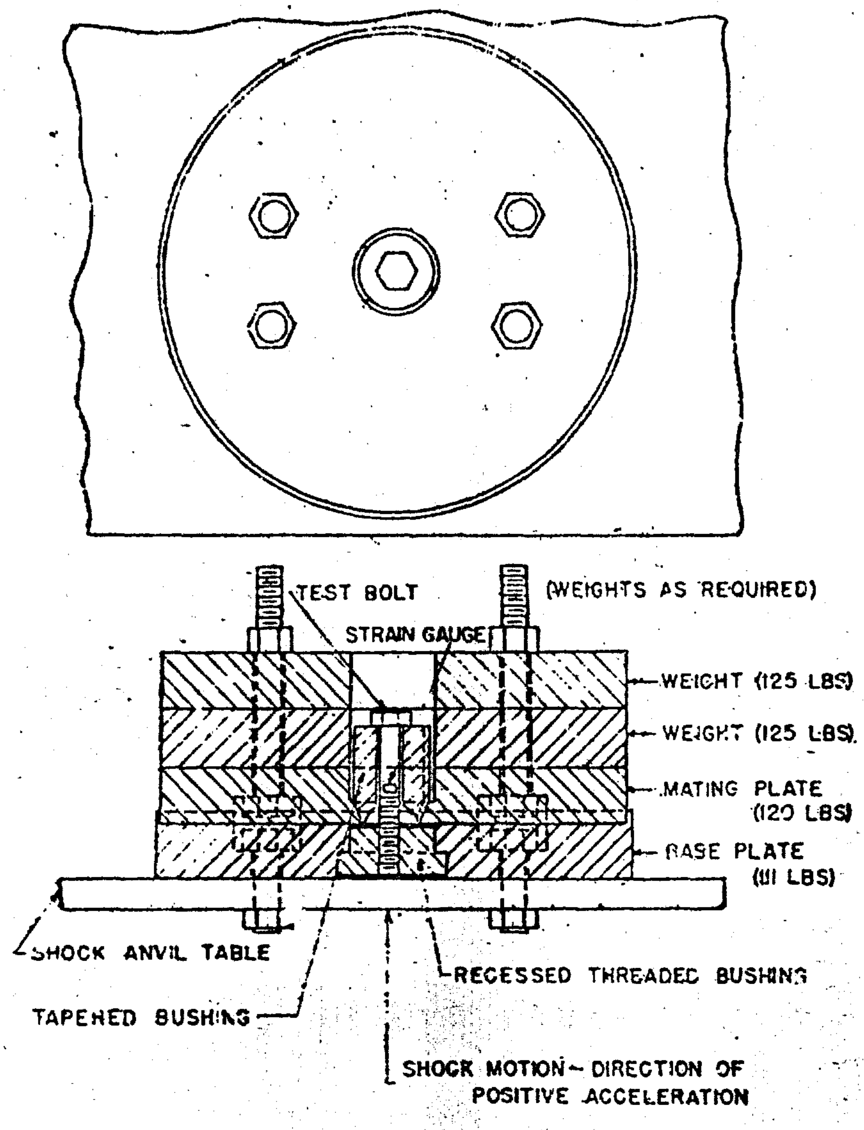


Fig. 4 - Loading arrangement for dynamic tests. Appropriate instrumentation was attached to the loading weights for measurement of load velocities and accelerations, and the shock machine anvil table was struck from below.

Two extremes of shipboard installation were simulated by different methods of attaching the base plate to the shock machine. In the first method, the base plate was fastened directly to the anvil table, providing very abrupt velocity changes. This type of shock is very similar to that experienced by equipments mounted near the hull of a ship subjected to underwater explosion. In the second method, the base plate was mounted on channels according to the normal specifications for shock tests of Naval equipments (21). To a large extent, this removes the abruptness of acceleration and deceleration noted in the first type of mounting, and is typical of that experienced by equipments at inboard locations. The flexibility of the channels, however, introduces strongly defined frequencies into the shock motions, which may be extremely damaging when they coincide with the natural frequencies of equipments or components. The two types of test mountings are illustrated in Figs 5 and 6, respectively.

The shock motions of the anvil table were kept as uniform as possible from blow to blow by maintaining the total load on the table constant for all tests. The hammer was dropped from a height of 2.25 ft, and the anvil table was restricted to an upward travel of 1.5 in. The weights of the loads restrained by the specimen bolts were either 169, 293, or 423 lb, and one bolt was tested with a load of 122 lb. Following each blow, the bolt was removed, and its elongation was measured. It was then replaced in the apparatus and tightened to a predetermined stress.

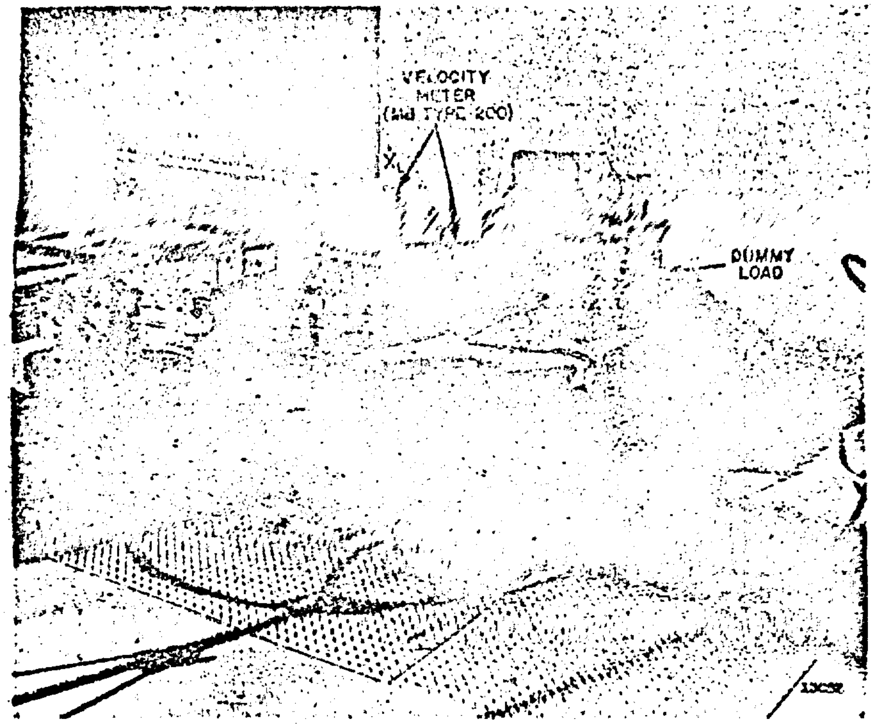


Fig. 5 - Dynamic test apparatus, as arranged for loads mounted directly on the shock machine anvil table. Two bolts are here under test, their restrained loads topped by velocity meters. The dummy loads between them enabled the total load on the shock machine anvil table to be held constant for both types of load-bolt mounting arrangements.

The measuring instruments were an SR-4 strain gage which was attached to the shank of the bolt immediately adjacent to the threads, an MB type 200 velocity meter fastened to the anvil table, and a quartz crystal accelerometer and/or an MB type 200 velocity meter attached to the load. The signals produced by these devices were recorded simultaneously. The instrumentation may be seen in Figs. 5 and 6.

Before each test blow, the bolt under test was tightened until an attached strain gage indicated a prestress of 25,000 psi. In the case of 1020 HR bolts, the prestress was reduced to 20,000 psi. The torque required to reach this stress when the bolt was first tightened was recorded, enabling the prestress to be approximated for later blows if the strain gage had failed. In the case of straight-shank bolts, where most of the elongation occurred in the exposed length of the thread, the strain gage usually survived the bolt. In the case of reduced-shank bolts, the gage usually failed after the first few blows, since elongation occurred almost exclusively in the shank, near where the gage was attached.

CHARACTERISTICS OF IMPACT TEST RECORDS

Figure 7 presents typical records obtained during tests of various bolts. Records of the velocity of the center of the anvil table exhibit a waveform approximating a step change of velocity with some

Fig. 6 - Dynamic test apparatus as arranged for loads mounted on channels. Here the base plate of Fig. 4 is secured to standard mounting channels. One bolt is shown in position for test.

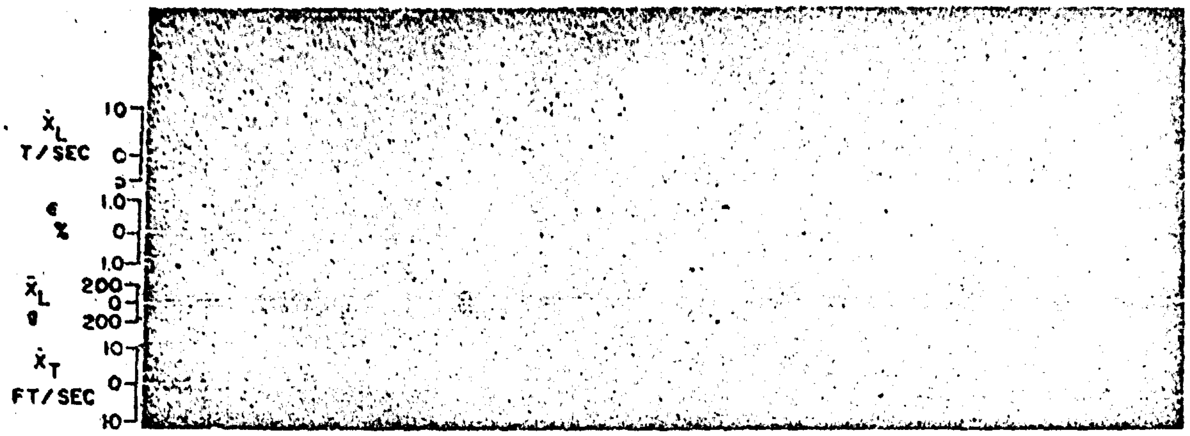
high-frequency modulation. The anvil table is accelerated upward for a period of about 1 millisecond, after which its average velocity is essentially constant at a value of about 6 ft/sec. When the anvil table reaches the limit of its permissible travel, it is abruptly restrained by the table holddown bolts, its velocity reversal taking 2 to 3 milliseconds. Timing was provided by an auxiliary 1-kc signal, or by blanking markers spaced at millisecond intervals.

When the load is mounted directly on the anvil table (Fig. 7a and 7b), its velocity record is essentially that of a high-frequency, single-degree-of-freedom system excited by a step change of velocity. The frequency of the load-bolt system varies from about 200 cps for 423-lb loads to 300 cps for 169-lb loads. In the case of an idealized, undamped system excited by a step velocity change V_1, the motion of the mass may be described by the expression

$$V_2 = V_1 [1 - \cos \omega_n t],$$

where V_2 is the velocity of the mass and ω_n is the natural circular frequency of the system. In these tests, the peak load velocities were found to be about 1.6 to 1.7 times the velocity of the anvil table, indicating that this simple system is a fair approximation to that which actually existed.

Records of load velocity in the case of channel-mounted loads (Fig. 7c) reveal a rather smooth sinusoidal motion at a frequency of about 60 cps. Abrupt velocity changes, due to stopping the anvil table, are isolated from the test bolt due to the low-pass filter action of the mounting channels. It was found under these circumstances that, for light loads, many of the bolts did not stretch plastically, so it was necessary to replace these loads by ones of 423 pounds before any plastic strain could be induced. Since the data from these bolts, when restraining 169-lb loads, consist entirely of zero average extensions per blow, they are not included in the graphs of Fig. 9, but are presented separately as Table A9.

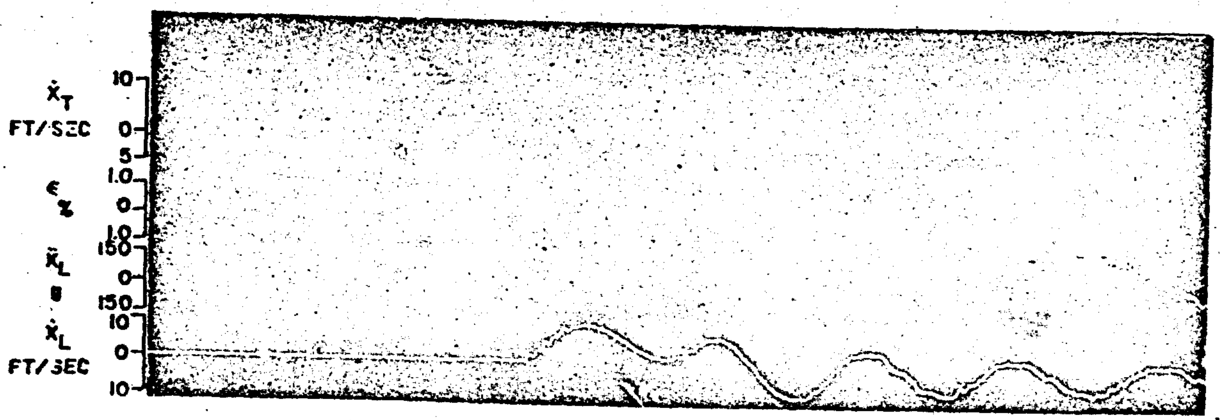


A - 1020 HR SHORT STRAIGHT - SHANK

293 LB TABLE - MOUNTED LOAD

B - 1020 CR LONG STRAIGHT - SHANK

169 LB TABLE - MOUNTED LOAD



C - 4140 SHORT REDUCED - SHANK

423 LB CHANNEL - MOUNTED LOAD

Fig. 7 - Typical dynamic test records. Timing is provided by a 1-kc auxiliary signal or by blanks at 1-ms intervals. An offset between channels is present due to the geometry of the recording system. The pips at the left of the records indicate the same instant of time. In part B, the millisecond blank immediately preceding the onset of activity is the same instant in all channels. The abrupt change in the anvil table velocity ($\dot{x}_T$) about 20 ms from its initial rise is due to the table striking the upper limit stops, and reversing its travel. The marked change in the nature of the load velocity ($\dot{x}_L$) caused by mounting the load-bolt system on channels is readily apparent in Fig. 7c. Load and anvil table velocities ($\dot{x}_L$ and $\dot{x}_T$, respectively) were measured by MB type 200 velocity meters, load acceleration ($\ddot{x}_L$) by a Westinghouse quartz accelerometer, and bolt strain (ϵ) by an SR-4 gage next to the threads and a dc bridge circuit.

When the load-bolt system is mounted directly on the anvil table, four major strain peaks are found (Fig. 7). Three of these occur during the rise time of the anvil table, while the fourth, and generally largest, coincides with the reversal of the table.

The first three peaks are caused by transient oscillations due to flexibility of the table which impose dynamic strains on the bolt before the anvil table reaches the upper limit of its travel. The maximum value of the first strain peak is of the same order of magnitude as that caused by table reversal, and is sufficiently large to extend well into the plastic range. The forces acting on a bolt at these times may be determined as the product of the weight restrained by the bolt and its negative peak of acceleration, which is shown on most of the records.

When the load-bolt system is mounted on channels, strain peaks appear at each period of negative load acceleration. Except for the 423-lb loads, these peaks are small and almost entirely elastic. With both methods of load mounting, the strain records are quite smooth, indicating that the higher frequencies observed in the load velocity and acceleration curves are local vibrations at the instrument locations that cause little strain in the bolt.

If the strain maxima for each blow are derived from the SR-4 records for several successive blows, they are found to decrease steadily. This effect is caused by the development of necking at a location some distance from the gage. Since reduced-shank bolts are subject to greater uniform strain than the straight-shank type, and short bolts are generally subject to greater strains than long bolts, this effect can be observed only for long, straight-shank bolts. This effect may be observed in the group of data in Table A8.

Although necking occurred in the threads of the straight-shank bolts, some permanent elongation occurred over the entire length of the bolt for the first two or three blows. Thereafter, the ratio of thread root area to shank area was reduced sufficiently to cause all yielding to take place in the exposed threads. Reduced-shank bolts, on the other hand, continued to strain plastically in the shank. As a result, strain gages were subjected to much greater strains in reduced-shank bolts, usually sufficient to cause gage failure during the first or second blow. Those attached to SAE 4140 bolts generally survived three of four blows.

Five of the SAE 1020 HR short, straight-shank bolts failed by shearing their threads; this was not observed in bolts of the other materials. These bolts are indicated by a T beneath the appropriate bars of Figs. 8 through 16.

One SAE 1020 HR long reduced-shank bolt elongated to such a degree that it could no longer be tightened; testing of this bolt was consequently discontinued. All of the 1020 HR straight-shank bolts failed in the threads, and all reduced-shank bolts failed about midway along the shank. All bolts showed reduction of area at the point of failure; this was greatest for the SAE 1020 HR bolts and least for SAE 4140.

It is usual, in the case of tests which rupture the specimen or bolt with a single blow, to present impact work, or its ratio to static work, as the quantity of interest. Under the conditions or repeated impact loadings, this quantity is difficult to determine, due to the uncertainty concerning the energy absorbed by the bolt for any particular blow. From the bolt strain and load acceleration curves, an estimate could be made for those blows for which records of these quantities exist, but a great deal of computation would be required, and a reasonable degree of accuracy could not ultimately be expected.

Measured values of the selected test parameters are shown on Figs. 8 through 16. Each blow is represented by a separate numbered bar. The values shown for average extension per blow are those observed for all blows except that which fractured the bolt. The extension for this last blow was usually about half that for any preceding blow, indicating that the bolts usually failed at an early stage of the last blow. The values given for the other properties are the averages of the values observed for all blows.

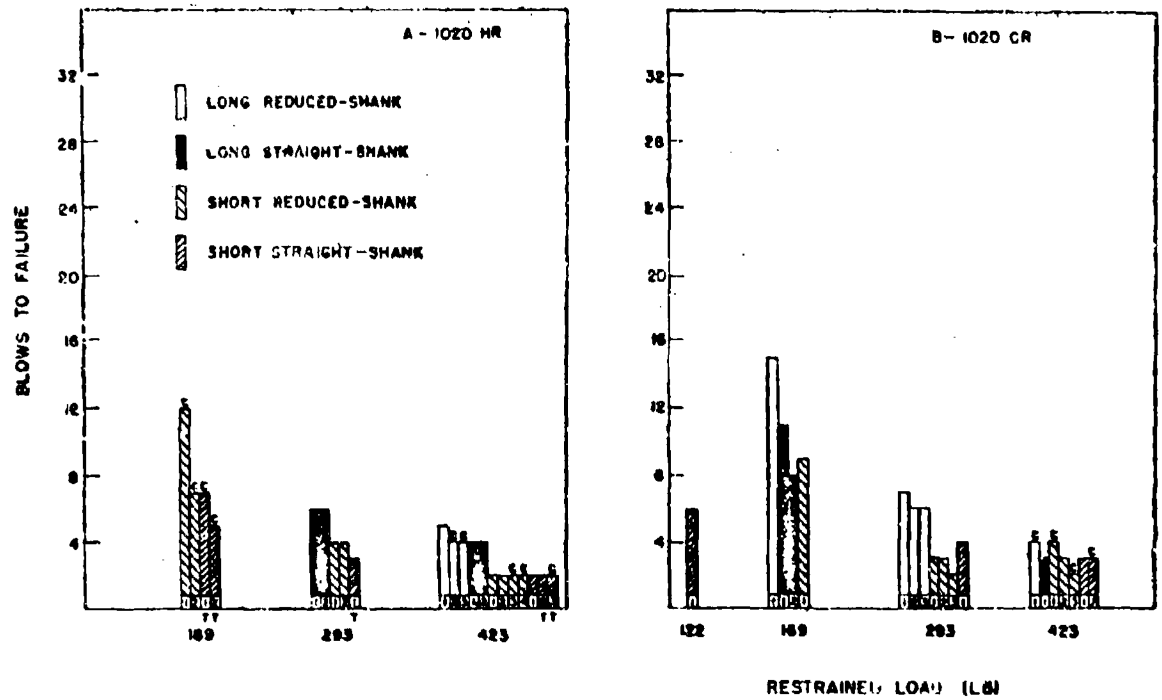
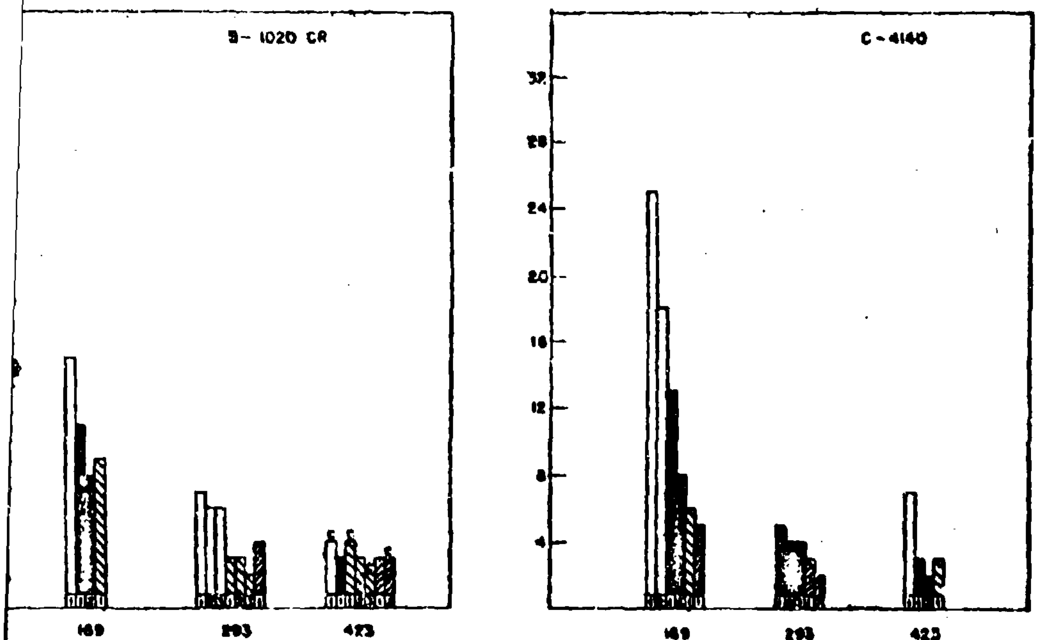


Fig. 8 - Blows to failure vs restrained load. In this and all the subsequent Figures, 9 through 16, each bolt is identi
appropriate bar. A bolt is thus identified by this number in all figures when the material, design, and restrained loa
tifies the same bolt through Figs. 8a, 9a, 10a, etc. at 16C lb. The coding of bolt design indicated in Fig. 8a is mainta
a bar in these graphs indicates that this load-bolt system was mounted on channels, while a "T" below a bar indic
threads rather than by actual fracture of the body of the bolt.



RESTRAINED LOAD (LB)

subsequent Figures, 9 through 15, each bolt is identified by a number boxed at the base of the figures when the material, design, and restrained load are the same; for instance, No. 1 iden- he coding of bolt design indicated in Fig. 8a is maintained throughout. A "C" appearing above mounted on channels, while a "T" below a bar indicates that this bolt failed by stripping the

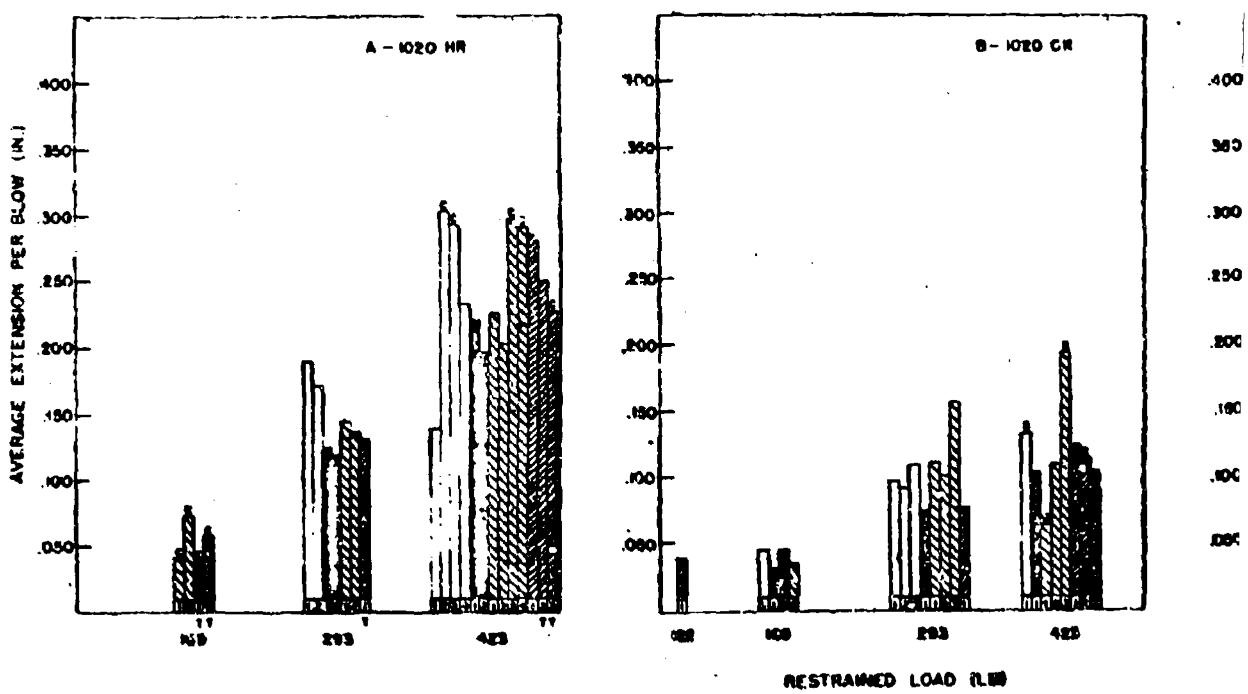
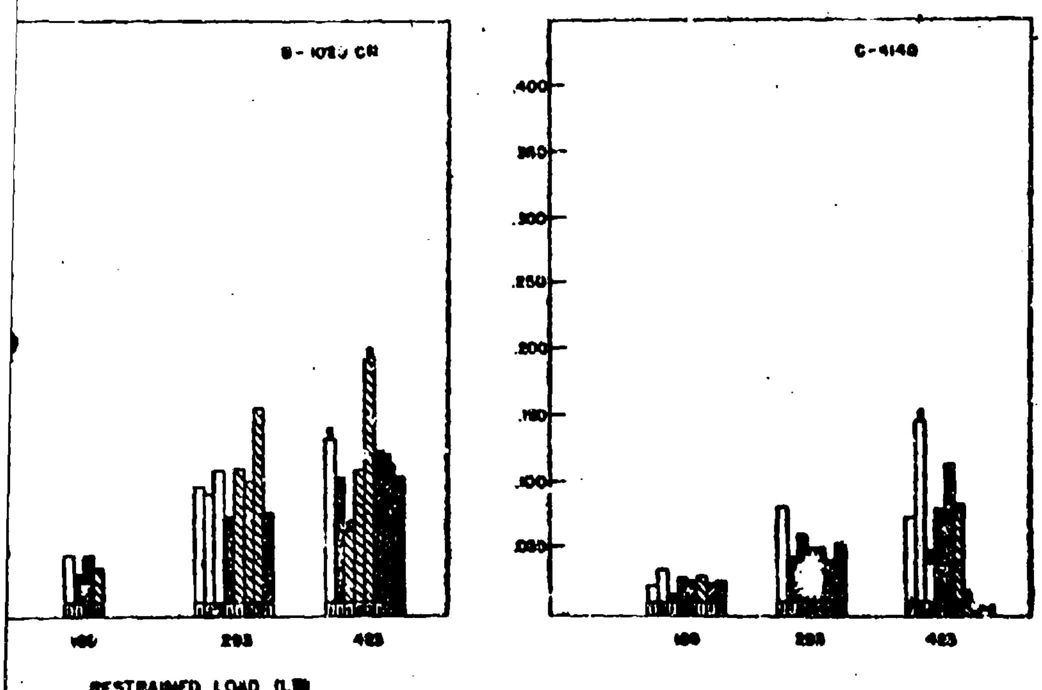


Fig. 9 - Average elongation per blow vs restrained load. This is the average value of the plastic elongation for each fractured (the bolt) being disregarded.



s the average value of the plastic elongation for each blow, the effects of the last blow (which
tured the bolt) being disregarded.

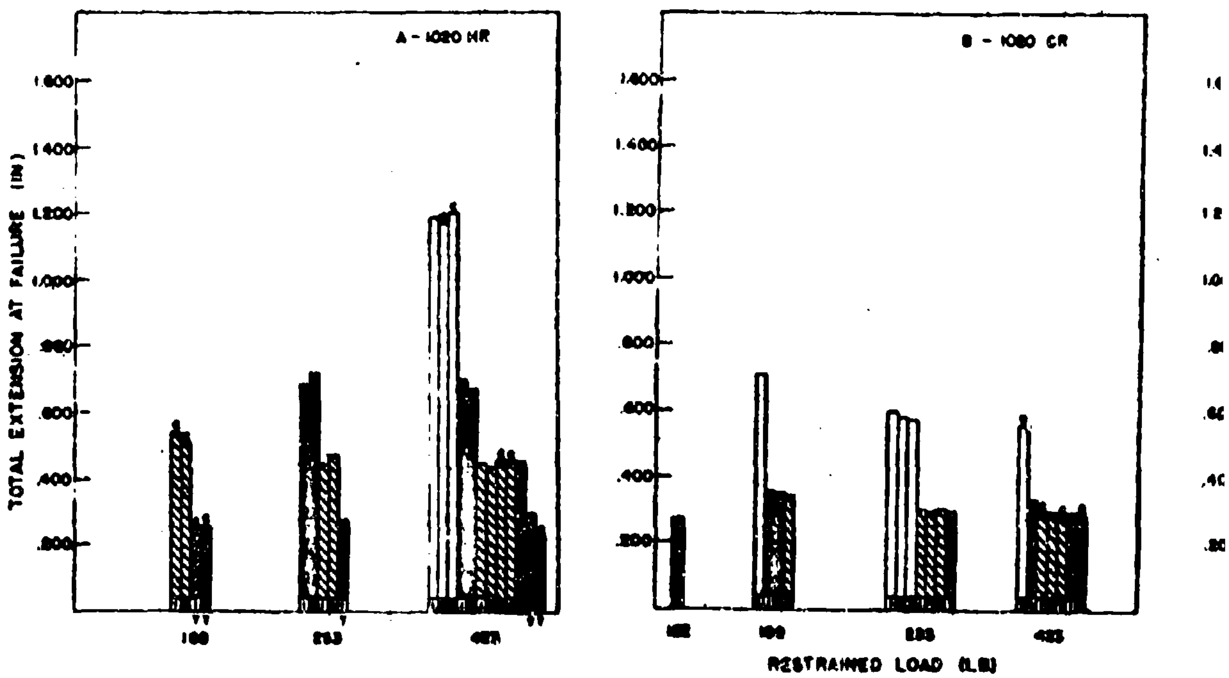
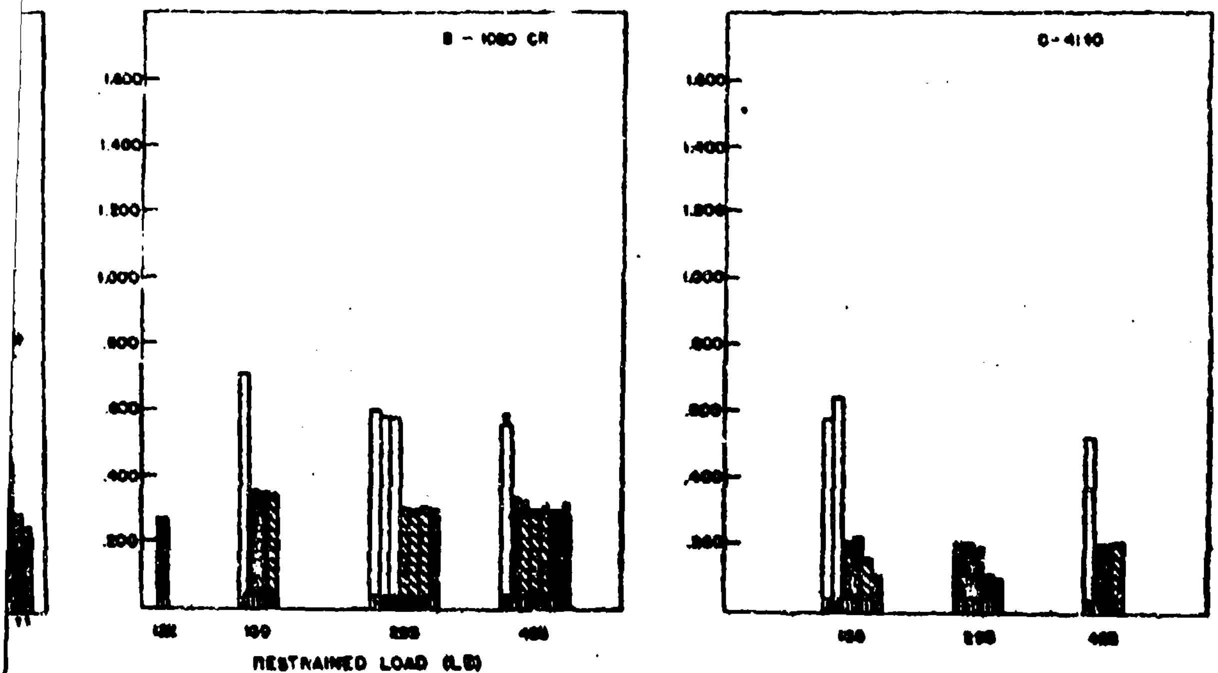


Fig. 10 - Total elongation at failure vs restrained load. This is the total plastic elongation acquired by the bolt durin
a dependence of this parameter on load for long reduced-shank bolts, and to a lesser extent for short reduced-shank



...ned load. This is the total plastic elongation acquired by the bolt during the course of test. It is interesting to note ...ong reduced-shank bolts, and to a lesser extent for short reduced-shank bolts, possibly indicating some strain-aging-

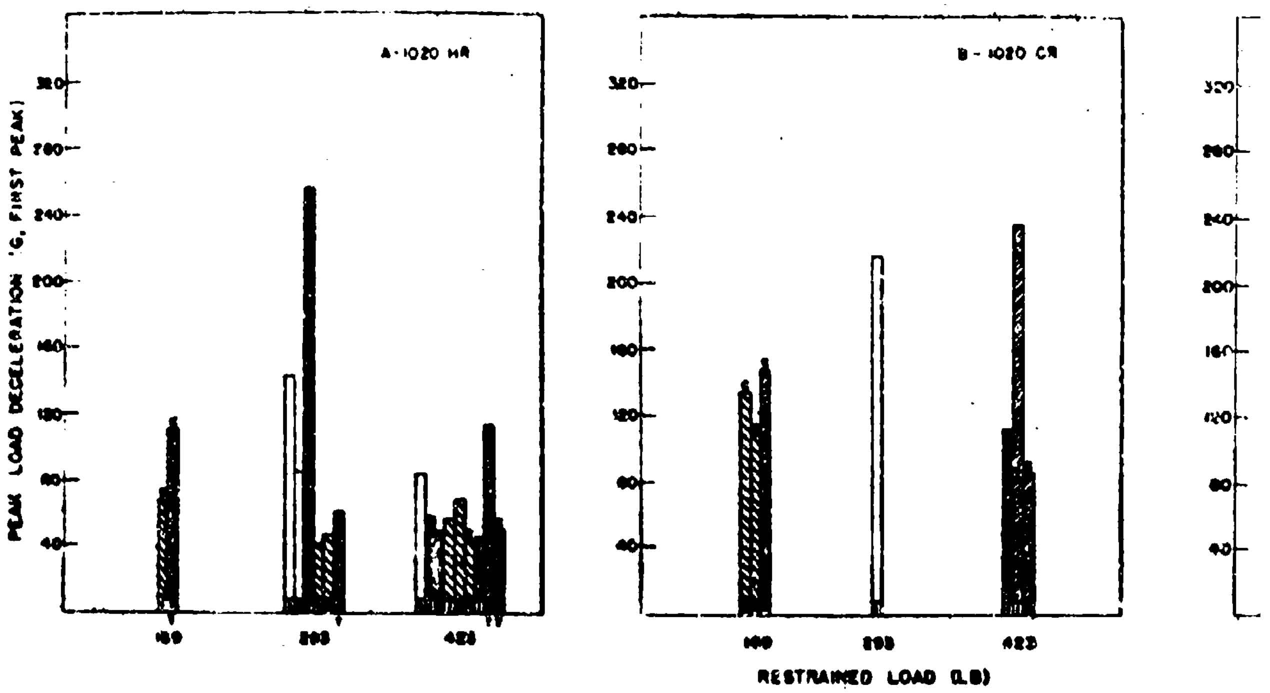
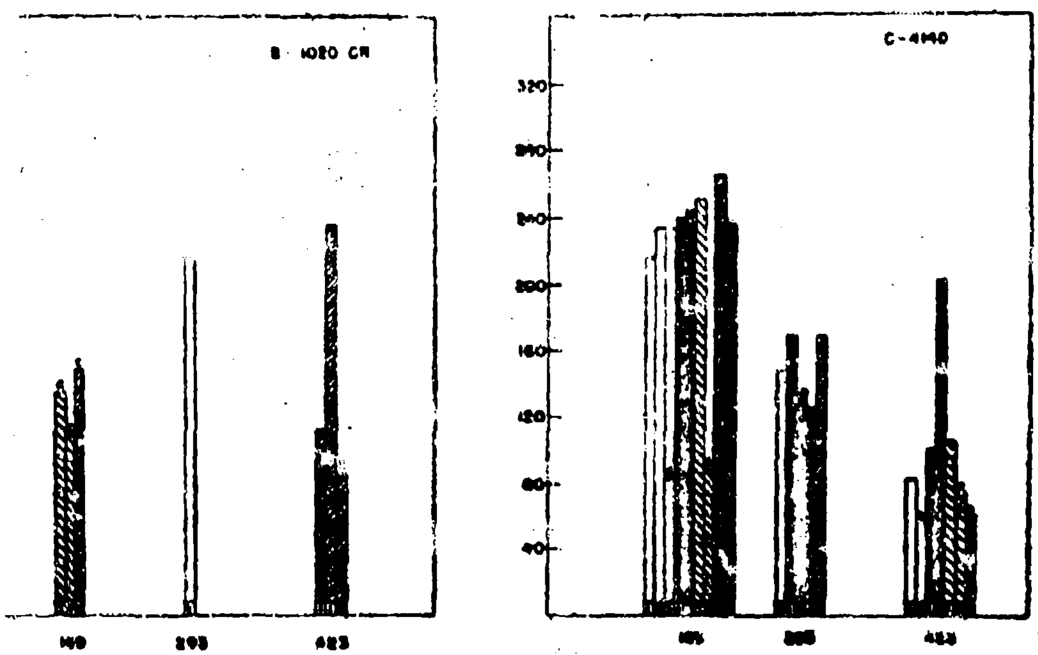


Fig. 11 - Peak load deceleration (first peak) vs restrained load. This quantity was measured by means of a quartz acc
undoubtedly includes the contribution of local vibrations, its value as a criterion of bolt performance is dubious. Refere
quencies observable in the load acceleration records ($\ddot{x}_L$) do not appear to a noticeable extent in the bolt strain record
major activity, immediately following the initial rise of the table (and hence load) velocities. The values shown here a



...d. This quantity was measured by means of a quartz accelerometer mounted on the load. Since it... value as a criterion of bolt performance is dubious. Reference to Fig. 7 reveals that the higher fre... not appear to a noticeable extent in the bolt strain records (8). The first peak is the first period of... this (and hence load) velocities. The values shown here are averaged over all blows.

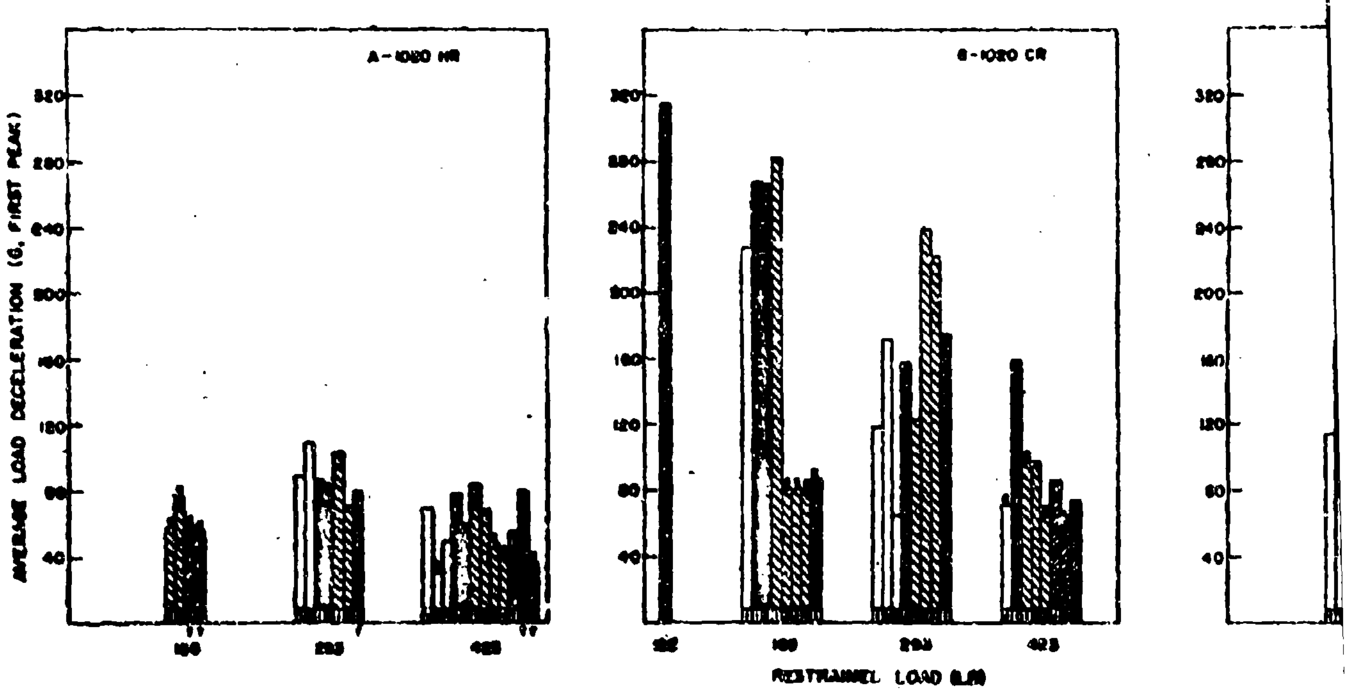
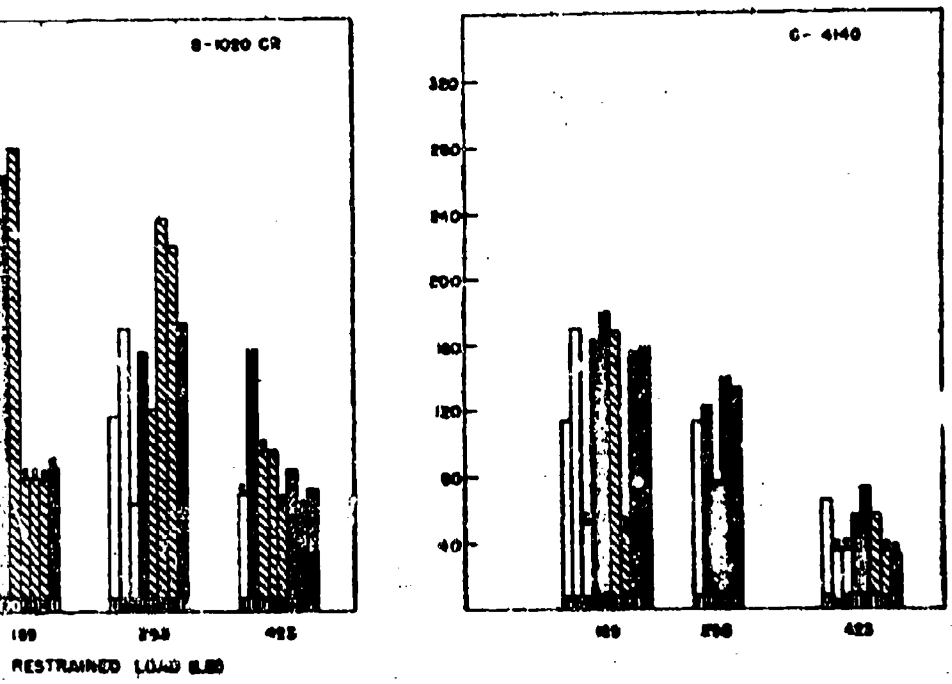


Fig. 12 - Average load deceleration (first peak) vs restrained load. This quantity is derived from the negative slope of the load ve
and hence is probably a better measure of the belt performance than the values given by the accelerometer. The values given



...is quantity is derived from the negative slope of the load velocity-time record θ_L, Fig. 7b.
...the values given by the accelerometer. The values given are the averages for all blows.

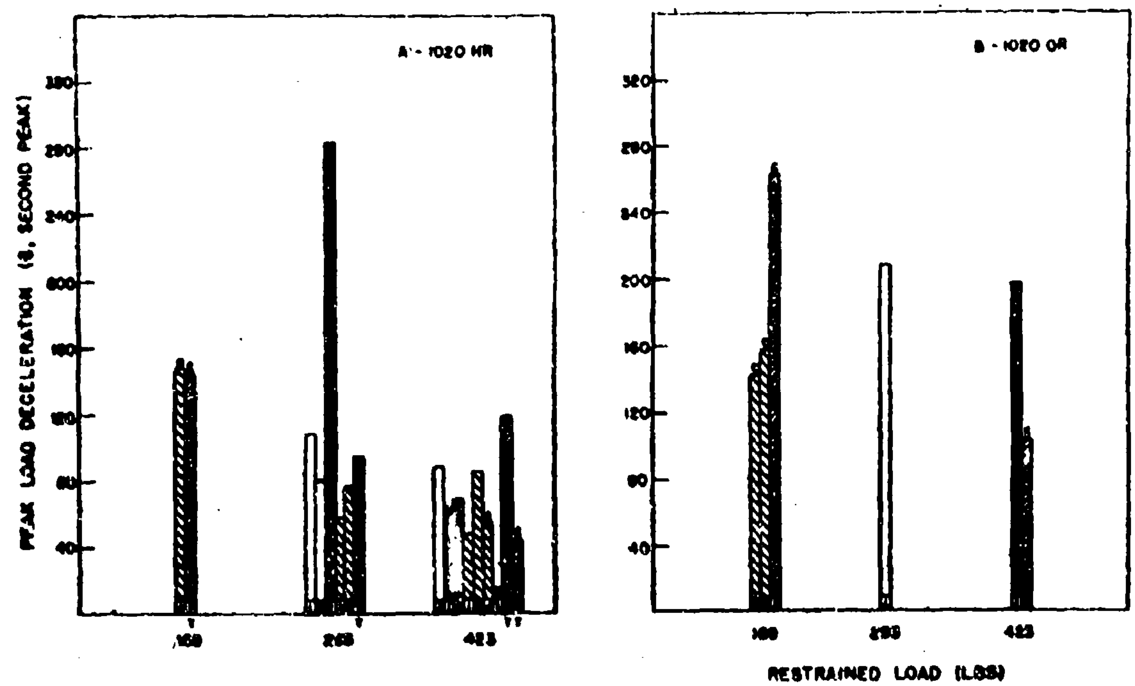
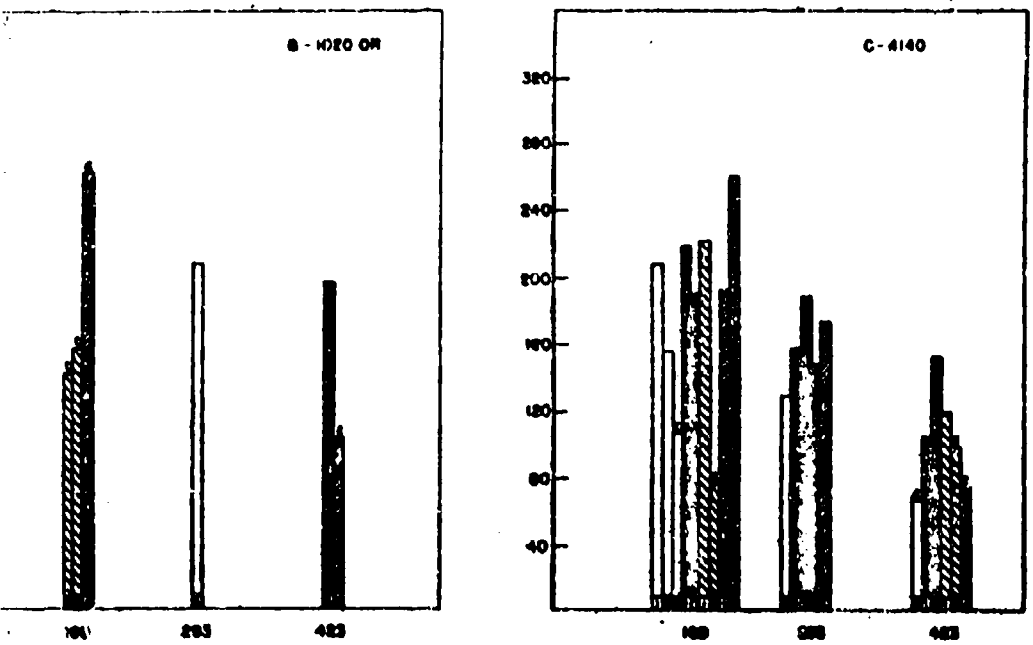


Fig. 13 - Peak load deceleration (second peak) vs restrained load. The second peak corresponds to the period
reversing its motion, due to striking the upper limit stops (Fig. 7). These values are a



load. The second peak corresponds to the period during which the shock machine anvil table is
the upper limit stops (Fig. 7). These values are averages for all blows.

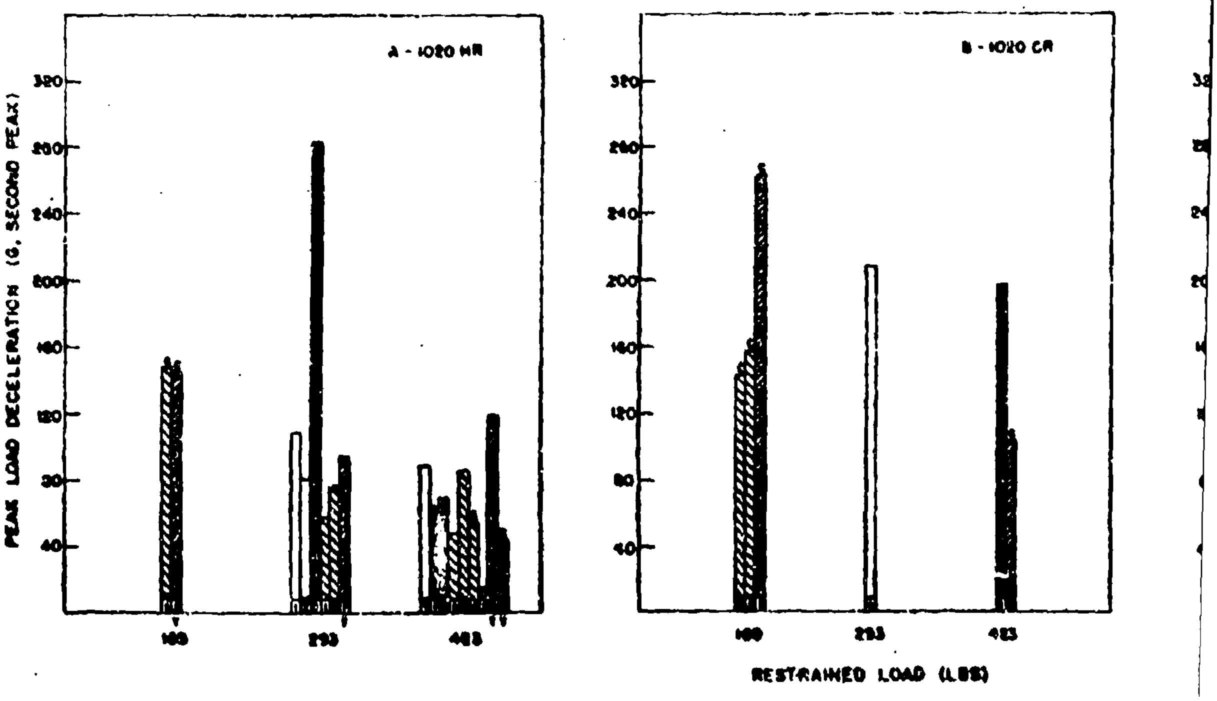
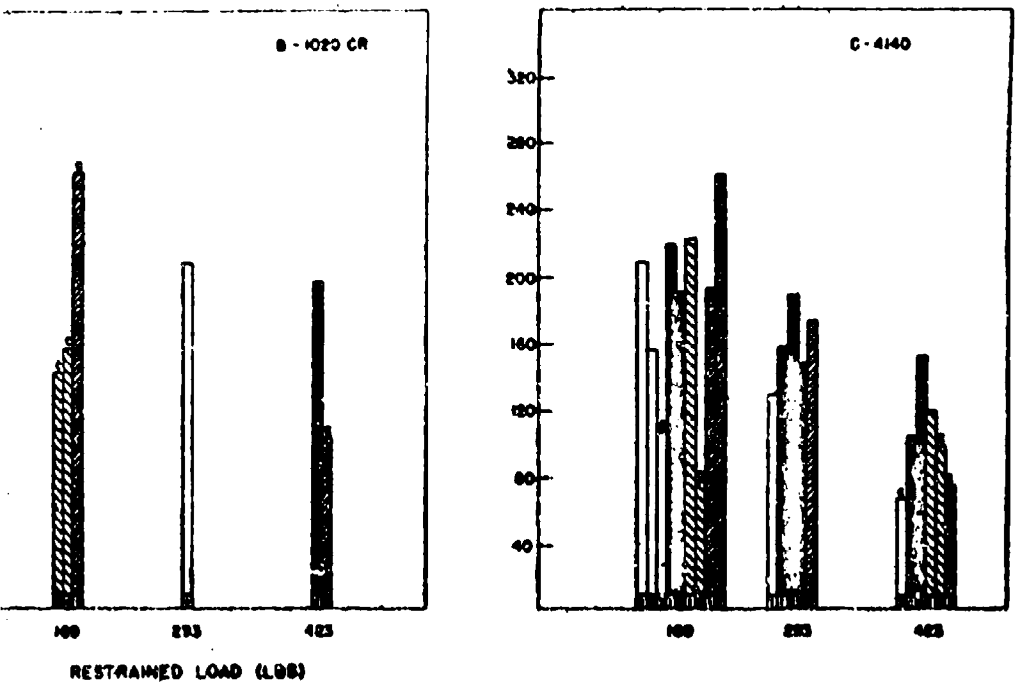


Fig. 13 - Peak load deceleration (second peak) vs restrained load. The second peak corresponds to the period du
reversing its motion, due to striking the upper limit stops (Fig. 7). These values are ave



load. The second peak corresponds to the period during which the shock machine anvil table is the upper limit stops (Fig. 7). These values are averages for all blows.

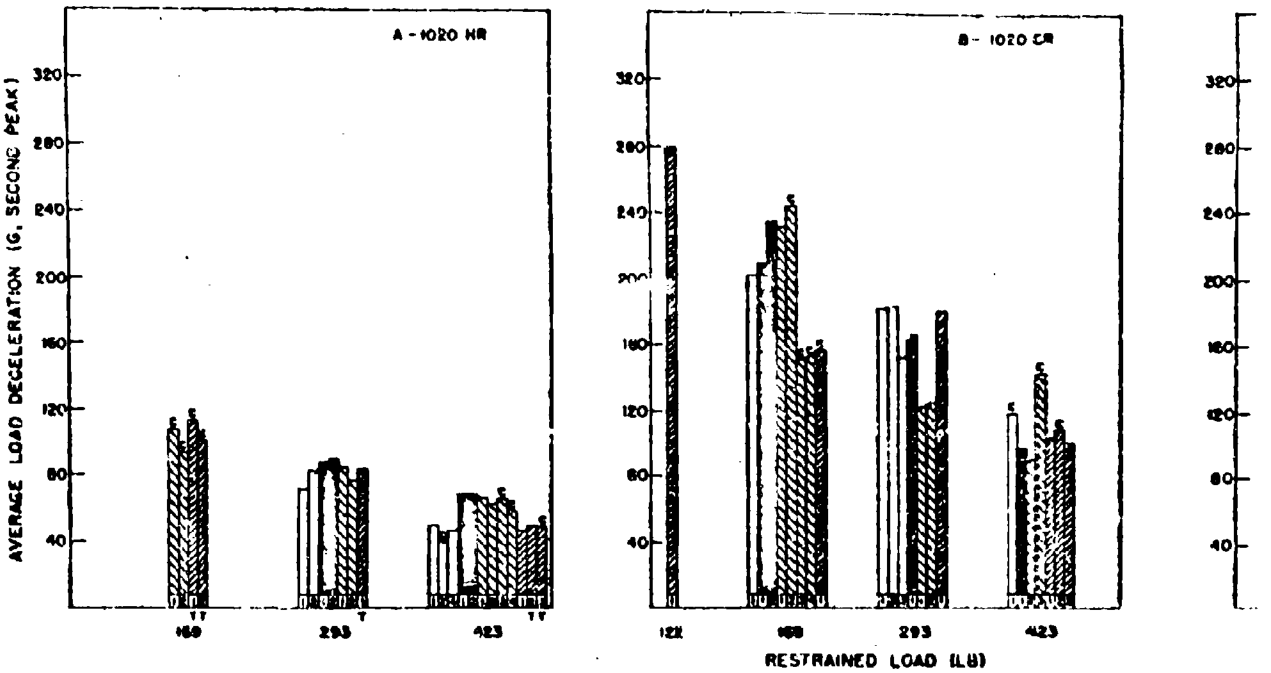
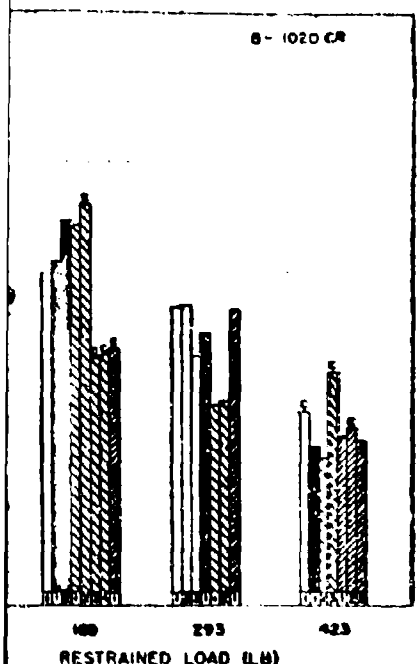
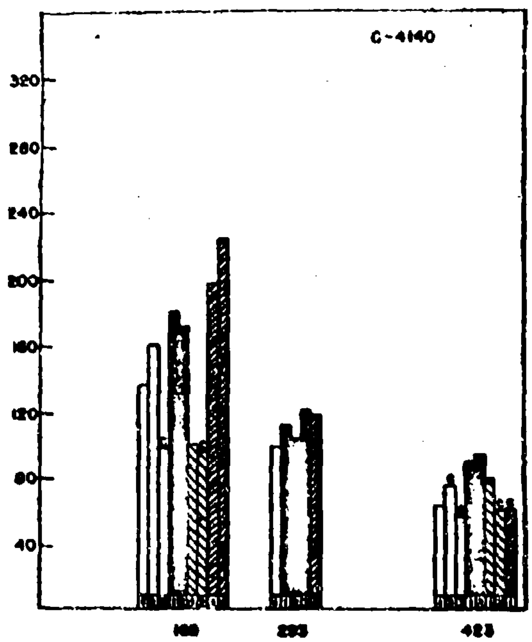


Fig. 14 - Average load deceleration (second peak) vs restrained load. It may be noted that decelerations during this pe
found during the first peak. The values shown are averages for all blows.





ed load. It may be noted that decelerations during this period are somewhat higher than those
t peak. The values shown are averages for all blows.

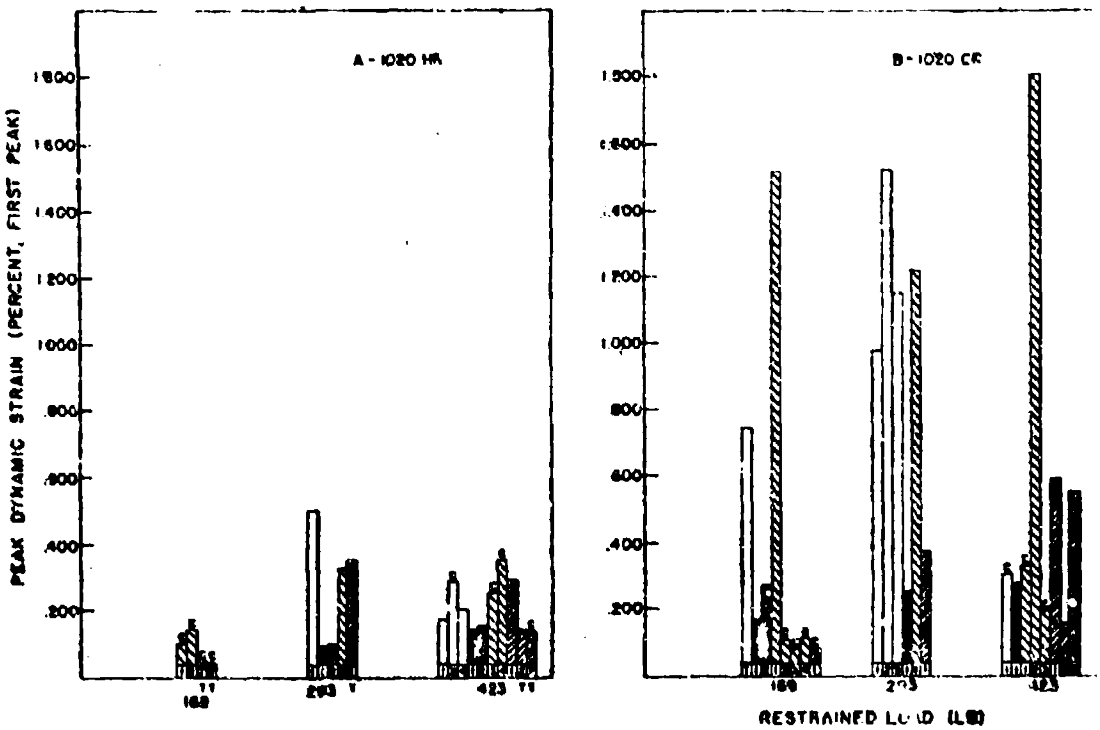
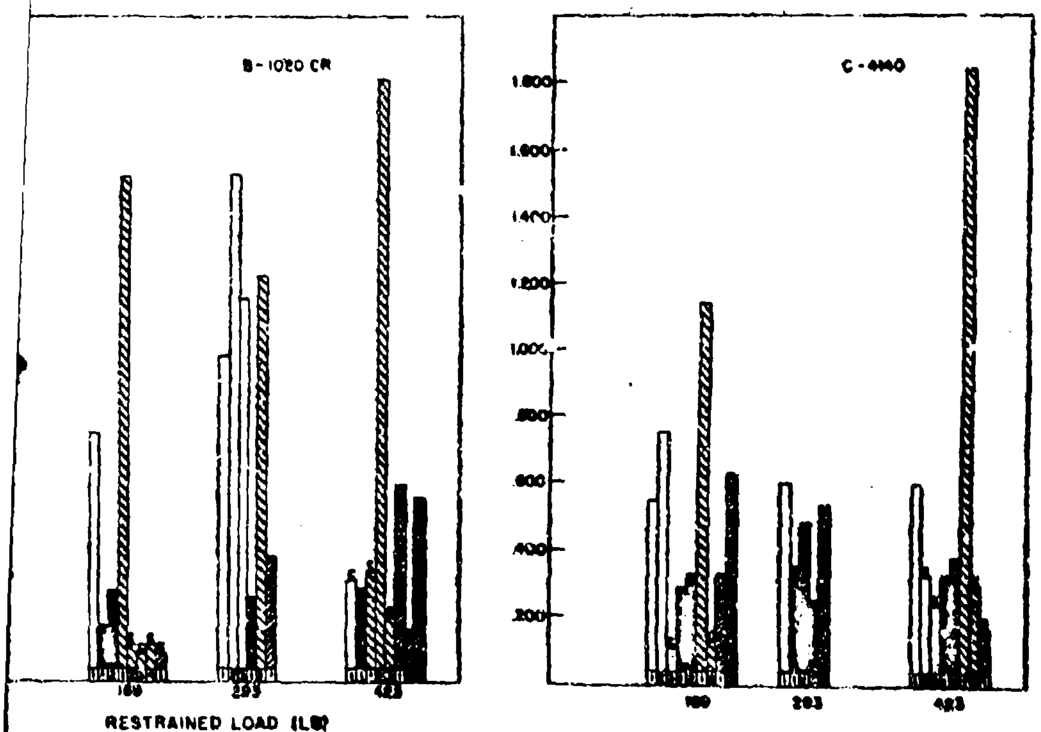


Fig. 18 - Peak dynamic strain (first peak) vs restrained load. Dynamic strain was measured by an SR
threads and an associated dc bridge. These values are averages



load. Dynamic strain was measured by an SR-4 gage attached to the bolt shank adjacent to the
lated dc bridge. These values are averages for all blows.

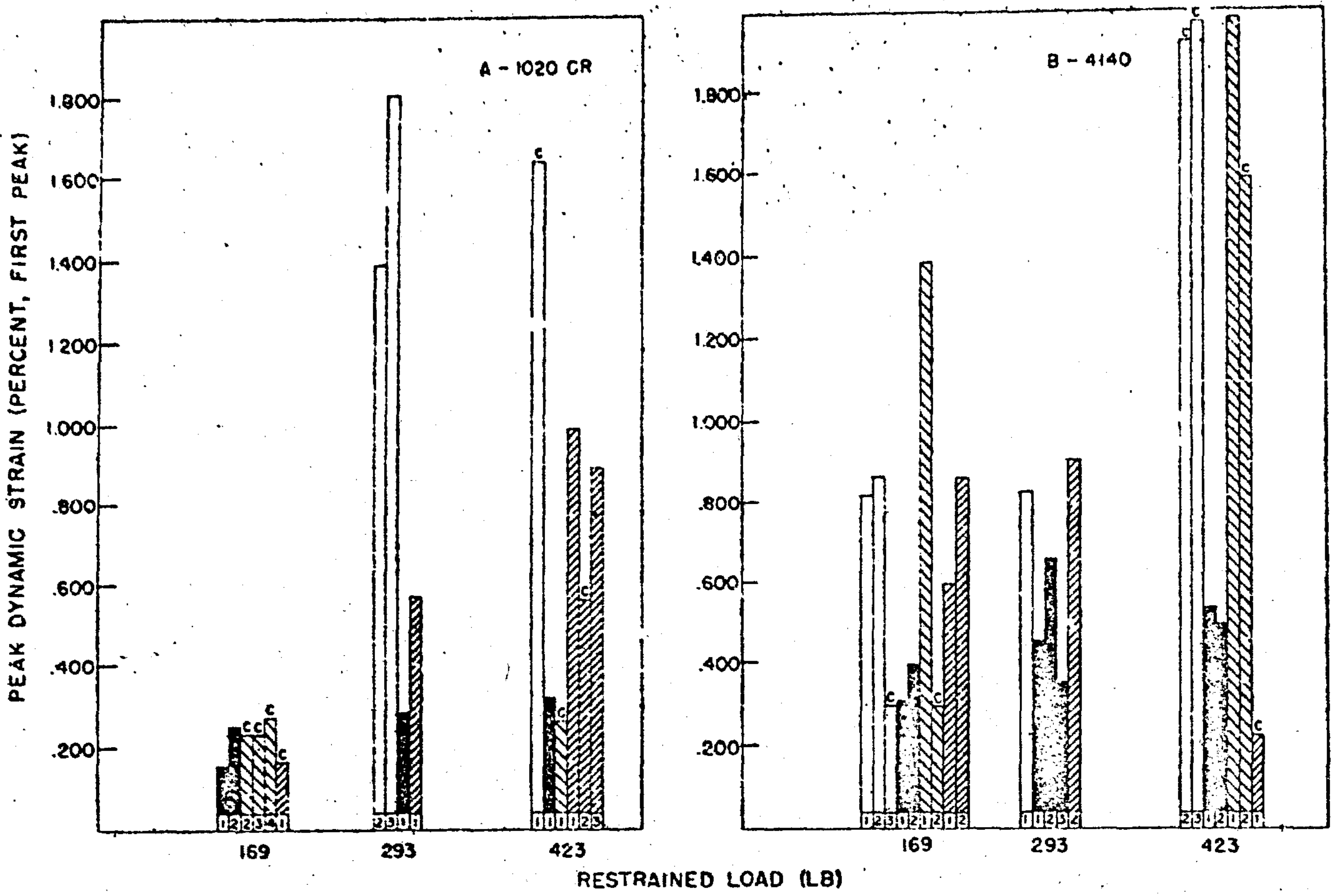


Fig. 16 - Peak dynamic strain (second peak) vs restrained load. A considerable increase in dynamic strain may be found during this period as compared with those of the first peak; in the case of 1020 HR bolts the increase was so great as to result in invariable failure of the gage. The values stated are averages for all blows.

It should be noted that the peak table and load velocities had little effect on the rate or magnitude of the strain experienced by the bolt. In addition, differences between these velocities do not accurately provide the velocity of deformation of the bolt, since anvil table or channel flexibilities permit the base plate of the testing rig to acquire velocities considerably different from those measured at the center of the anvil table. The maximum inertia load supported by the test bolt is the product of the peak negative acceleration (or the maximum negative slope of the velocity-time curve) and the mass of the load, and is equal to the maximum force transmitted by the bolt. This quantity is dependent upon the strength of the bolt. Considering the designs of the bolts tested, it is evident that the gages attached to reduced-shank bolts will be at locations where maximum strain occurs, so that readings from such gages may be expected to vary with the maximum inertia load on the bolt, while gages attached to straight-shank bolts will be exposed primarily to the elastic part of the strain, so that any relation between peak inertia load and peak strain measured in these bolts will be much less pronounced. That this is found experimentally may be seen from the data of Figs. 11 through 16.

Records of bolt strain and acceleration of table-mounted loads (Fig. 7) show four major periods of activity; of these, however, the period immediately following the initial acceleration of the anvil table and that associated with the anvil table reversal generally have more effect than the other two. Consequently, data are presented for these two periods only, the former being referred to as the "first peak" and the latter as the "second peak". The second peak is somewhat greater in magnitude than the first, and consequently plays a proportionately greater role in the determination of the properties of bolts as measured in these tests. In all graphs, the values stated for the test parameters are the average values for each blow during which these quantities were measured.

IMPACT TEST RESULTS

Blows to Failure

Since the velocity of the load relative to the anvil table was found to be about the same for all loads and bolts, being varied principally by the load-mounting arrangement, it may be assumed that all bolts tested with the same load and load-mounting arrangement absorbed about the same amount of energy during a typical blow, and that this amount of energy increased about linearly with the load. General trends drawn from Fig. 8 concerning the number of blows to failure indicate that

a. Reduced-shank bolts will withstand more blows before failure than equivalent straight-shank bolts.

b. Long bolts will withstand more blows before failure then equivalent short bolts.

c. Short reduced-shank bolts are only slightly better than short straight-shank bolts; the advantage of the reduced-shank bolt becomes considerable as the bolts become long.

d. Long straight-shank bolts have only a slightly longer life under the given shock conditions than equivalent short straight-shank bolts.

e. The number of blows a bolt of any design and material can survive will vary inversely with the load multiplied by a constant determined by the material, bolt design, and load mounting.

f. Other control parameters being the same, SAE 4140 bolts will survive the greatest number of blows, followed in order by SAE 1020 CR and SAE 1020 HR.

It is interesting to note that with loads of 423 pounds, bolts of all designs, materials, and load mounting arrangements survive a comparable number of blows (about 2 to 4), although the variation is very large (from 5 to 25) when the lighter loads are used. Mounting the load on channels appears both to increase the individual variation between results of identical bolts, and to amplify the dependence of "blows to failure" on load. Some bolts, for channel-mounted arrangements and for small loads, could not be fractured; on the average, those bolts which were fractured with channel-mounted arrangements survived about the same number of blows as similar bolts with the same loads table-mounted.

Average Elongation per Blow

The bar graphs of Fig. 9 illustrate the elongation per blow, and permit the following generalizations:

a. For a given condition, the bolt elongation per blow, for a successive series of blows exclusive of the blow causing fracture, is approximately constant.

b. The major factors affecting the bolt elongation per blow were the bolt material, the load, and the load-mounting arrangement.

c. Minor variations in bolt elongation were caused by bolt design. These effects were more pronounced for greater loads. In general, average elongations per blow were greater for reduced-shank than for straight-shank bolts, and short bolts generally had greater elongations per blow than similar long bolts.

d. There was no correlation between elongation per blow with channel- and table-mounted arrangements.

e. As expected, the average elongation per blow was greater for SAE 1020 HR bolts, followed by SAE 1020 CR and SAE 4140 bolts.

f. In general, long reduced-shank bolts showed greater average elongations than bolts of the other designs.

Total Elongation at Failure

Figure 10 illustrates the total elongation at failure, from which the following generalizations are made:

a. Reduced-shank bolts undergo greater total elongation than straight-shank bolts, and long bolts undergo greater total elongation than short bolts.

b. The increased total elongation of long bolts as compared to short bolts was less noticeable in straight-shank than in reduced-shank bolts.

c. Total elongation was found to be a constant of the material and the bolt design, and was little affected by changes of the load and load mounting.

d. Total elongations of SAE 1020 HR bolts were the greatest followed by 1020 CR and 4140 bolts.

It should not be inferred from this that the total elongation will not change if the rate-of-strain is drastically altered. Table 1, which illustrates the total elongation to fracture for similar bolts under static and dynamic conditions, shows generally increased elongation under dynamic conditions, with a greater percentage increase for reduced shank bolts.

An interesting feature of these graphs is that the total elongations of long reduced-shank bolts of all materials are greater for 169-lb loads than with other loads. Since with this load, bolts of this design had by far the longest lifetime (most blows before fracture) of all bolts tested, this is possibly due to a strain-aging process. Other attempts to show strain aging were not successful.

Load Deceleration, Peak and Average

In the data shown in Figs. 11 through 14, peak decelerations have been derived from the maximum negative signals of the load accelerometer, and "average" decelerations from the average slope of the load velocity-time records. This latter figure is more significant, since the higher frequencies present in the former are ignored. These higher frequencies are local vibrations which do not appear appreciably in the strain records of the bolts. The average decelerations indicate the maximum values that can be effected under these load-bolt arrangements and for these shock conditions. The bolts were undergoing plastic flow during the stage of maximum deceleration.

Load decelerations encountered during the second peak (the peak resulting from the reversal of the table velocity, Fig. 7) were generally somewhat greater than those found during the first peaks; in particular, a very large increase (about 200-300 g) was found for peak decelerations of loads restrained by short straight-shank bolts of both SAE 4140 and SAE 1020 CR steel. While individual variations of similar bolts were also more pronounced, the general characteristics were much the same as those found during the first peak.

TABLE 1
Comparison* of Static and Dynamic Properties of Bolts

Material	Type of test	Bolt length (in.)	Restrained load (lb)	Shank type	Blows to failure	Total elongation (in.)	σ_{max} (psi x 10^3)
1020 HR	Dynamic	4¼	169	Reduced	-	-	-
			169	Straight	-	-	-
			293	Reduced	-	-	85.8
			293	Straight	6	0.698	58.9
			423	Reduced	5	1.185	74.0
			423	Straight	4	0.684	70.0
		2	169	Reduced	-	-	-
			169	Straight	-	-	-
			293	Reduced	4	0.456	78.0
			293	Straight	3	0.275	55.8
			423	Reduced	2	0.442	84.3
			423	Straight	2	0.378	60.8
	Static	4¼		Reduced		1.056	49.8
				Straight		0.618	52.8
		2		Reduced		0.464	65.6
				Straight		0.250	50.9
	D/S Ratio	4¼		Reduced		1.1	1.6
				Straight		1.1	1.2
		2		Reduced		1.0	1.2
				Straight		1.3	1.1
1020 CR	Dynamic	4¼	169	Reduced	15	0.706	117.2
			169	Straight	10	0.356	104.2
			293	Reduced	6	0.584	169.0
			293	Straight	-	-	109.1
			423	Reduced	-	-	-
			423	Straight	3	0.333	149.3
		2	169	Reduced	9	0.347	148.2
			169	Straight	6	0.276	120.5
			293	Reduced	3	0.302	155.5
			293	Straight	4	0.300	124.0
			423	Reduced	3	0.297	132.7
			423	Straight	3	0.296	96.0
	Static	4¼		Reduced		0.415	90.8
				Straight		0.311	75.1
				Reduced		0.280	97.7
		2		Straight		0.274	77.5
	D/S Ratio	4¼		Reduced		1.6	1.6
				Straight		1.1	1.6
		2		Reduced		1.1	1.5
				Straight		1.1	1.5
4140	Dynamic	4¼	169	Reduced	21	0.610	83.1
			169	Straight	10	0.222	71.2
			293	Reduced	-	-	98.1
			293	Straight	4	0.208	84.1
			423	Reduced	7	0.523	82.7
			423	Straight	2	0.208	85.9
		2	169	Reduced	6	0.166	84.1
			169	Straight	5	0.114	74.4
			293	Reduced	-	-	-
			293	Straight	2	0.112	84.1
			423	Reduced	3	0.215	97.9
			423	Straight	-	-	-
	Static	4¼		Reduced		0.378	102.2
				Straight		0.186	89.2
		2		Reduced		0.119	109.6
				Straight		0.117	94.1
	D/S Ratio	4¼		Reduced		1.5	0.9
				Straight		1.1	0.9
		2		Reduced		1.6	0.8
				Straight		1.0	0.8

*Values given are average values from all bolts restraining table-mounted loads.
σ_{max} = maximum stress, computed from velocity records, and does not include data from the blow which fractured the bolt.

Peak Dynamic Strain

The dynamic strain was determined by a gage attached at a definite location on a bolt, and indicates only the average strain that occurs over that section. The sensitive element consisted of an SR-4 strain gage affixed to the bolt immediately above the threads, and hence removed from the region of necking of all bolts. The data presented are consequently more nearly proportional to the uniform part of the strain than to the total elongation. The following generalizations may be made from the strain records and the tabulations of Figs. 15 and 16:

a. Under the same experimental conditions, reduced-shank bolts underwent a greater uniform strain than straight-shank bolts, and short bolts experienced a greater strain than long bolts.

b. The variation of indicated strain with bolt length was greater in reduced-shank bolts, where the distance between the gage and the region of necking varied, than in straight-shank bolts, where necking occurred at the same distance from the gage regardless of bolt length. This effect was less marked in SAE 4140 bolts than in those of the other materials, since in this case only a small amount of necking occurred.

c. While SAE 1020 HR bolts acquired the greatest total elongation (Fig. 9), this was due largely to necking; the uniform strain was lowest for SAE 1020 HR bolts.

Strains measured during the second peak (reversal of table velocity) were much greater than those found during the first peak, particularly in the case of 1020 HR bolts. In bolts of this material, local strains were sufficiently high to cause failure of the gage.

CONCLUSIONS

The use of reduced-shank bolts results in more desirable shock characteristics, particularly when bolts are fairly long. The effect of reducing the shank is not great for short bolts. Since reduced-shank bolts can still be tightened after having been stretched to an unsafe degree, it may be necessary that their lengths be checked after conditions of shock that require retightening, and that they be replaced when their percent elongations reach some critical value, determined primarily by the material of the bolts. For straight-shank bolts, the plastic strain occurs in the threaded region, so such a bolt can no longer be tightened after much plastic flow.

While it is known (11) that the advantages of high tensile alloys with respect to the mild steels may decrease under conditions of shock, there is still a considerable advantage in the use of properly heat-treated high tensile alloys. Of the three materials tested, the SAE 4140 possessed the most favorable properties. SAE 1020 HR should not generally be used unless some shock protection is desired by virtue of its ability to provide large deformations.

Such stress risers as threads and scratches, that require a relatively small amount of plastic flow for their relief, have comparatively little effect on the performance of bolts under shock conditions. It should not be inferred from this that stress risers such as cutouts and corners in structures, that can only be relieved by a large amount of plastic flow, are unimportant.

Aging processes appear to have a definite effect on the properties of bolts under impact conditions, but this can only be qualitatively determined from the data of these tests. It appears that if more strain-aging time is allowed, some improvement in the number of blows to failure, or ability to absorb energy, results.

The test results, summarized in Table 1, have been found to be essentially in agreement with published data (11), particularly in the case of reduced-shank bolts. The ratios of dynamic to static elongations, and the ratios of dynamic to static maximum stresses, exhibit considerable variation with bolt design. In general, SAE 4140 bolts exhibit the greatest increase in ductility under dynamic conditions, while that of 1020 HR and 1020 CR bolts increases but little. SAE 1020 CR bolts, however, show the greatest increase in maximum stress, while 4140 bolts show the somewhat anomalous characteristic of an actual decrease in this quantity. This is probably due, at least in part, to the fact that the dynamic stress-strain curve of this material decreases considerably for blows following the first; for example, the curves of Reference (11) indicate that while the dynamic proportional limit during the first blow is 1.64 times the static, during the second blow this ratio drops to about 1.44. This effect does not occur to such an extent in either SAE 1020 HR or 1020 CR bolts.

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* * *

APPENDIX A

Some Static and Dynamic Properties of Representative Bolts

In this section, tables of sundry properties of interest are presented. Table A1 classifies the bolts according to shank type and length, and shows the number of bolts of each type tested. Tables A2 through A7 present the data from the series of static tests of both bolts and standard 0.505-in.-diameter specimens. Table A8 shows some dynamic properties of representative 4-1/4-in.-long straight-shank bolts, and Table A9 presents the test data for such bolts as were not greatly deformed under their test conditions.

TABLE A1
Number of Bolts Tested

Material	Number				
	RL	SL	RS	SS	Total
1020 HR	6	4	8	6	24
1020 CR	5	4	12	10	31
4140	7	9	4	5	25
Total	18	17	24	21	80

Note: RL - long, reduced-shank bolt
SL - long, straight-shank bolt
RS - short, reduced-shank bolt
SS - short, straight-shank bolt

TABLE A2
Static Properties of 1020 HR 0.505-In.-Diameter Specimens*

Specimen	Original Diameter (in.)	E (psi x 10^6)	σ_y (psi x 10^3)	σ_u (psi x 10^3)	σ_f (psi x 10^3)	ϵ_f (%)	Reduction of area (%)
1	0.5054	30.8	41.1	62.0	47.8	40.5	62.1
2	0.5054	30.0	42.1	59.1	42.4	42.5	65.7
3	0.5048	30.6	38.7	57.5	40.5	42.5	68.8
4	0.498		36.5	63.7	49.6	29.5	61.4
5	0.5051	31.2	40.4	62.6	46.9	41.0	62.6
6	0.489		39.3	63.4	49.8	29.0	61.0
Average		30.6	39.7	61.5	46.2	37.5	63.6

*σ_y = yield point
σ_u = maximum stress
σ_f = stress at failure
ϵ_f = strain at failure

TABLE A3
Static Properties of 1020 HR Bolts*

Specimen	Bolt Type	Original Diameter (in.)	E (psi x 10^6)	σ_y (psi x 10^3)	σ_u (psi x 10^3)	σ_f (psi x 10^3)	Total elongation (in.)
1	LR	0.656	31.9	38.1	50.8	42.6	1.070
2	LR	0.656	29.6	36.9	40.8	39.3	1.043
3	LS	0.750	30.8	30.6	55.0	42.3	0.612
4	LS	0.750	35.1	29.9	52.6	42.6	0.625
5	SR	0.656	37.2	39.9	65.6	52.9	0.450
6	SR	0.656	34.0	39.3	66.6	53.6	0.400
7	SS	0.750	29.4	29.8		50.9†	0.255
8	SS	0.750	36.2	30.0		50.9†	0.244
Average			31.8	34.4	56.1	45.9	

*σ_y = yield point
σ_u = maximum stress
σ_f = stress at failure
LR = long, reduced-shank bolt
LS = long, straight-shank bolt
SR = short, reduced-shank bolt
SS = short, straight-shank bolt
†Thread failed

TABLE A4
Static Properties of 1020 CR 0.505-in.-Diameter Specimens*

Specimen	Original Diameter (in.)	E (psi × 10^6)	σ_y (psi × 10^3)	ϵ_y (%)	σ_u (psi × 10^3)	ϵ_f (%)
1	0.5045	29.0	53.0	0.183	96.0	12.5
2	0.505	29.2	47.5	0.169	83.0	18.0
3	0.504	29.1	51.25	0.176	90.0	15.5
4	0.505	29.0	48.75	0.168	87.75	15.5
5	0.505	29.0	48.5	0.167	82.5	18.0
6	0.5045	29.4	50.0	0.170	91.5	16.5
7	0.505	29.4	50.0	0.170	90.0	16.5
8	0.505	27.8	50.0	0.180	88.25	18.5
9	0.504	29.4	48.75	0.165	90.0	16.5
10	0.504	26.1	46.5	0.178	85.75	18.5
11	0.505	28.0	50.0	0.172	94.0	17.0
Average		28.6	48.5	0.173	88.8	16.6

*σ_y = proportional limit
ϵ_y = strain at proportional limit
σ_u = maximum stress
ϵ_f = strain at failure

TABLE A5
Static Properties of 1020 CR Bolts*

Specimen	Bolt type	Original diameter (in.)	E (psi × 10^6)	σ_y (psi × 10^3)	σ_u (psi × 10^3)	σ_f (psi × 10^3)	Total elongation (in.)
1	RL	0.656			89.8	61.5	0.428
2	RL	0.656			90.0	61.8	0.409
3	RL	0.656	28.4	62.0	90.5	63.6	0.424
4	RL	0.656			90.2	62.1	0.409
5	RL	0.656			90.5	62.4	0.409
6	RL	0.656	30.2	59.3	93.9	66.6	0.418
7	SL	0.750	31.6	45.3	74.4		
8	SL	0.750			73.6	50.5	0.320
9	SL	0.750			73.5	50.0	0.322
10	SL	0.750	28.1	52.1	73.9	53.2	0.311
11	SL	0.750	29.7	51.9	80.1	56.9	0.282
12	RS	0.656			97.8	74.0	0.201
13	RS	0.656			97.6	74.0	0.200
14	SS	0.750			79.0	56.6	0.263
15	SS	0.750			76.0	52.3	0.206
Average			29.6	54.1	84.7	60.5	

*σ_y = proportional limit
σ_u = maximum stress
σ_f = stress at failure
RL = long, reduced-shank bolt
SL = long, straight-shank bolt
RS = short, reduced-shank bolt
SS = short, straight-shank bolt

TABLE A6
Static Properties of 4140 0.505-in.-Diameter Specimens*

Specimen	Original diameter (in.)	E (psi × 10^6)	σ_y (psi × 10^3)	σ(0.1%) (psi × 10^3)	σ_u (psi × 10^3)	σ_f (psi × 10^3)	ϵ_f (%)
1	0.505	27.5	26.8	82.9			
2	0.508	27.5	14.3		107.1	89.5	13.0
3	0.508	25.9	17.5	76.5	107.1		14.5
4	0.507	28.5	24.3	75.3	111.7	98.6	10.5
5	0.506	26.1	52.2	87.0	109.2	96.0	12.5
6	0.505		44.9		104.6	87.9	13.5
7	0.505		52.9		104.1	89.4	13.5
8	0.5055		33.9		111.1	98.2	10.5
9	0.5055		36.4		109.1	94.1	13.5
Average		27.1	33.7	80.4	108.6	93.4	12.7

*σ_y = proportional limit
σ(0.1%) = stress corresponding to 0.1% plastic strain
σ_u = maximum stress
σ_f = stress at failure
ϵ_f = strain at failure

TABLE A7
Static Properties of 4140 Bolts*

Specimen	Bolt type	Original diameter (in.)	E (psi × 10^6)	σ_y (psi × 10^3)	σ(0.1%) (psi × 10^3)	σ_u (psi × 10^3)	Total elongation (in.)
Group I (1 SR4)							
1	RL	0.656	28.0	17.8	64.1	101.0	0.387
2	SL	0.750	27.2	43.1	77.0	89.0	0.104
3	RS	0.656	23.7	56.4	90.1	109.8	0.162
4	SS	0.750	28.9	38.6	84.0	94.2	0.067
Group II (2 SR4's)							
1	RL	0.656	26.5	38.5	74.6	103.5	0.369
2	SL	0.750	30.2	15.8	70.6	89.5	0.180
3	RS	0.656	25.0	38.5	78.7	109.5	0.076
4	SS	0.750	29.6	31.7	77.0	94.0	0.168
Average			27.2	36.0	77.0	98.9	

*σ_y = proportional limit
σ(0.1%) = stress corresponding to 0.1% plastic strain
σ_u = maximum stress
RL = long, reduced-shank bolt
SL = long, straight-shank bolt
RS = short, reduced-shank bolt
SS = short, straight-shank bolt

TABLE A8
Some Dynamic Properties of 48-in.-Long, Straight-Shank Bolts Restraining Table-Mounted Loads*

Material	Type of test	Restrained load (lb)	Blow number	σ_y (psi x 10^3)	σ_{max} (psi x 10^3)	Strain at SR 4(%) max.	Strain at SR 4(%) plastic	Strain at SR 4(%) Total plastic	Bolt elongation (in.) per blow	Bolt elongation (in.) total
10[illegible] HR	Dynamic	293	1	>54	59.7				0.141	0.141
			2						0.101	0.242
			3						0.107	0.349
			4						0.111	0.460
			5						0.133	0.593
			6†						0.120	0.713
	Static			30.2	52.8					0.618
	Max. dynamic			>54	59.7					0.713
1020 CR	Dynamic	169	1		92.9	0.26	0.08	0.08	0.018	0.018
			2		112.4	0.19	0.04	0.12	0.026	0.044
			3	>99	113.6	0.25	0.03	0.15	0.022	0.066
			4	>64	85.7	0.15	0.02	0.17	0.027	0.093
			5	>75	99.1	0.20	0.05	0.22	0.025	0.118
			6	>55	97.9	0.12	0.03	0.25	0.029	0.147
			7	>65	130.1	0.17	0.0	0.25	0.026	0.173
			8	>74	137.0	0.16	0.01	0.26	0.063	0.236
			9	>63	125.8	0.14	0.02	0.28	0.039	0.275
			10	>50	87.6	0.11	0.03	0.31	0.041	0.316
			11†						0.043	0.359
	Static			49.8	75.1					0.311
	Max. dynamic			>99.0	130.1			0.31		0.359
4140	Dynamic	169	1		106.3	0.57	0.12	0.22	0.030	0.030
			2	>103	64.6	0.40	0.06	0.28	0.028	0.058
			3		76.5	0.47	0.11	0.39	0.041	0.099
			4		73.4				0.023	0.122
			5	>94	63.9	0.38	0.01		0.025	0.147
			6	>84	68.5	0.29	0.07		0.025	0.172
			7	>81	61.2	0.28	0.06		0.030	0.202
			8†						0.027	0.229
	Static			29.4	89.2					0.186
	Max. dynamic			105	106.3					0.229

*Maximum stress computed from velocity records
†Fractured

TABLE A9
Dynamic Test Data for Undeformed Bolts, All Loads Channel Mounted*

Material	Bolt type	Restrained Load (lb)	σ_{max} (psi x 10^3)	No. of blows	Average elongation per blow (in.)	Total elongation reached (in.)	Remarks
1020 CR	LR	169	120.9	4	0	0	
	SS	169	74.5	3	0	0	
	SR	169	75.4	3	0	0	
	SR	169	99.1	3	0	0	
4140	LR	169	48.0	4	0.003	0.006	All elongation caused by first 2 blows
	SR	169	47.0	3	0.001	0.003	All elongation caused by first blow
	SS	420	57.1	3	0.004	0.008	First blow caused 0.[illegible]-in. extension, next 2 0.001-in. each.

*σ_{max} = maximum stress, computed from velocity records and averaged over all blows.
LR = long, reduced-shank bolt
SR = short, reduced-shank bolt
SS = short, straight-shank bolt

[illegible]

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Naval Research Laboratory. Report 4827.
PROPERTIES OF BOLTS UNDER SHOCK LOADING, by E. W. Clements.
37 pp & figs., September 17, 1956.

Four designs of bolts have been prepared from SAE 4140, SAE 1020 hot-rolled, and SAE 1020 cold-rolled steels, and subjected to typical shipboard shock motions while sustaining loads of various magnitudes. Bolt designs provided ratios of shank area to thread root area of 1.3/1 and 1/1 in each of two shank lengths. Such quantities as the velocity and acceleration of the suspended load, the velocity of the shock machine anvil table, and the dynamic strain and plastic elongation of the specimen bolt have been measured. Comparisons of static and dynamic stresses and elongations have been made to reveal how their relationship is affected by variation of bolt geometry and material. In general, the use of reduced shanks has been found to result in more desirable shock properties, particularly when the bolt length is fairly great. The improvement is smaller when the bolt length is short. Bolts of SAE 4140 steel have been found usually to possess a more desirable combination of properties than those of the other steels tested.

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1. Bolts - Failure
2. Bolts - Shock Resistance
3. Bolts - Test Results
I. Clements, E. W.

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